The Construction Of The Queensferry Crossing

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Summary

The Queensferry Crossing (Figure 1) is a cable-stayed bridge over the Firth of Forth between North and South Queensferry in Scotland. It is the third crossing in this vicinity, standing alongside the Forth Road Bridge (1964) and the Forth Rail Bridge (1890).

Figure 1 – The Queensferry Crossing, Scotland, in February 2017.

The bridge was conceived as a replacement for the existing suspension bridge. Inspections undertaken during 2005 had shown severe cable corrosion. Predictions indicated that heavy goods vehicles could be prohibited as early as 2017 with a closure to all vehicles in 2021 if the rate of corrosion continued. Transport Scotland commissioned studies for a new crossing culminating, in 2011, in the award of a design and build contract to a multi-national joint venture known as Forth Crossing Bridge Constructors, FCBC [2], to build a cable-stayed bridge. The Crossing includes a 2090m

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[1] The author was employed by American Bridge with responsibility for the design, checking and support to procurement, installation, operation and dismantling of the temporary works required to manufacture and construct the cable-stayed bridge and north approach viaduct.

[2] Main contractor - FCBC: American Bridge-Hochtief-Dragados-Morrison Construction. Designer: Ramboll-Gifford-Leonhardt, Andra und Partner-Grontmij. Design checker: AECOM-Scott Wilson.

long, three-pylon cable-stayed bridge with two main spans of 650m and twin fans of cables located centrally. The pylons are post-tensioned concrete. The deck is an orthotropic steel box, with a post-tensioned concrete running surface 40m wide. The overall length of the crossing is 2.7km. This paper presents the construction methods adopted for the production and erection of the deck of the cable-stayed bridge, with a particular focus on the temporary structures and operations developed in order to take delivery, from ships, of the partially completed steel deck units, complete the concrete deck, transport the sections and erect them into their suspended locations around 60m above the water level.

Keywords

Cable-Stayed Bridge; Bridge Construction; Construction Methods; Temporary Works.

Introduction: Recent History

The Forth Road Bridge, a suspension bridge opened in 1964, was found to have suffered advancing corrosion to the main cables. Remedial measures were taken, including opening the cable for inspections and the installation of a dehumidification system to dry the cables, slow down and eventually all but stop the corrosion rate. Despite this, studies carried out initially in 2003 and subsequently updated found that loading restrictions may be necessary by 2017 and the crossing may have to close in 2021. As the only vehicle crossing in the area, the nearest upstream being at Kincardine, some 25km away, and a major transportation artery, the Scottish Government, through their agency, Transport Scotland, initiated studies into a potential Replacement Crossing.
In December 2007, with Government commitment given to construct a new bridge crossing the Firth of Forth, a Jacobs-Arup joint venture carried out advanced studies to determine location, architecture, structural form and also design and construction criteria for the new crossing. Apart from the span arrangement some further notable features were fixed by the Employer regarding the deck and cable stays.

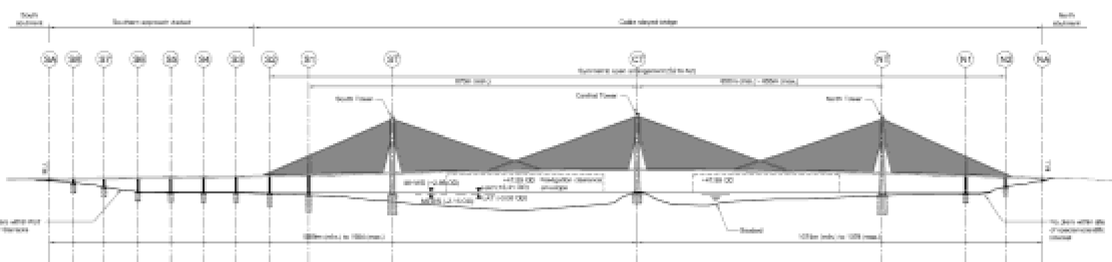

Figure 2 – General arrangement of the Queensferry Crossing.

The twin planes of cables are centrally located between the traffic carriageways, permitting elegant single-stemmed towers. The stay fans cross over at mid-span, providing an interesting architectural detail but also providing additional stiffness to the completed deck (Figure 2). The deck is comprised of a single box section over the

extent of the cable-stayed bridge, however, beyond the stay supported deck, the carriageways are separate, with a gap between them.
The tender process first chose a shortlist of two consortia as preferred bidders, and asked them to develop their designs and prices in a competitive dialogue process throughout 2010. The contract was awarded to FCBC on 18th April 2011.

Design and Build Contract

The contract scope included the entire crossing and the road connections into the existing motorway networks to the north and south of the River Forth. The design, independent design check and the construction were all included in a single contract and the joint venture of construction companies sub-contracted separate joint ventures for design and for the independent design check.
The design and checking scope was divided into sections: marine foundations, land foundations, towers, piers, cable-stayed bridge, approach viaducts and network connections (being the roads, interchanges and viaducts required to connect the new bridge to the existing motorway network). The construction was also divided roughly along similar lines, with 30% of the contract value being allocated each to American Bridge, Dragados and Hochtief, and Morrison Construction gaining 10% of the contract value, a total price of GBP 790 million (Table 1).

Table 1 – Division of Scope within Main Participants.

SCOPE	DESIGN	DESIGN CHECK	CONSTRUCTION
Marine Foundations	LAP	AECOM	Hochtief
Land Foundations	Gifford	AECOM	Dragados
Towers	LAP	AECOM	Hochtief
Piers	Gifford	AECOM	Dragados
Cable-Stayed Bridge	Ramboll	AECOM	American Bridge
Approach Viaducts	Gifford	AECOM	Dragados/American Bridge
Network Connections	Grontmij	Scott Wilson	Morrison Construction

Leonhardt, Andra und Partner (LAP) carried out the global structural modelling for the cable-stayed bridge and the approach viaducts. Each designer carried out local modelling for the elements being designed under their scope.
Transport Scotland retained Jacobs-Arup to oversee the construction, forming what was known as the Employer's Delivery Team (EDT). Their duties included detailed planning, technical reviews and construction monitoring. The design joint venture was also present on site (DSR) with a team charged with overseeing quality and workmanship. The process of specification and certification of materials, methods and control of installation, although carried out by FCBC, was overseen by the DSR, providing a fully documented record of the construction and compliance to specification.
Changes to the specimen design were proposed by the contractor, while preserving the desired architectural form and features stipulated by the client. The most significant change to the design was the change from a full width orthotropic box with either

orthotropic or concrete deck, to a post-tensioned concrete deck with 4m cantilevers, making the steel box significantly narrower (Figure 3). Additionally, the specimen design had illustrated piled foundations for all marine foundations with the exception of Beamer Rock, which was used for the central tower, bearing onto the rock island. In all, three marine foundations were constructed using caissons (Figure 4) and seven were constructed using sheet-piled coffer dams.

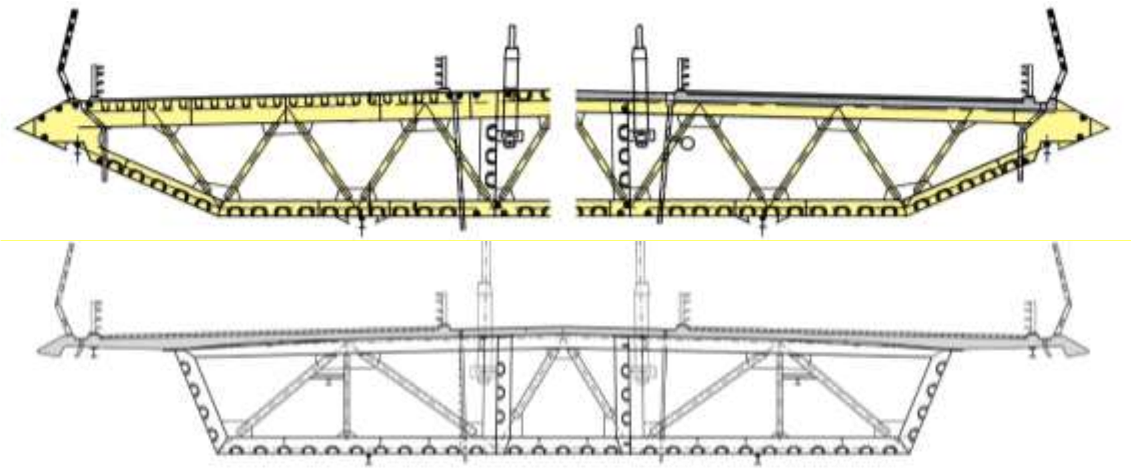

Figure 3 – Cable-stayed bridge deck cross sections, specimen design (above) and adopted design (below).

Figure 4 – Caissons during manufacture and shipping to the bridge site. (Photo: New Civil Engineer)

Focus On Suspended Deck Construction

The cable-stayed bridge steelwork, comprising segments with bottom and side plates, internal webs and cross frames weighing up to 325 tonnes each and 16.2m long, was fabricated in China and delivered to site during 2014-2015 on four ships, most with on-board cranes. The main temporary works for the deck support at the towers and the deck erection gantries were fabricated by the same company and brought together with the

permanent works. In all, this part of the scope supplied approximately 22,000 tonnes of permanent steelwork and 4 000 tonnes of temporary steelwork.
Each ship off-load was carried out as a continuous two to three-day operation, with transportation around the yard being by Self-Propelled Modular Transporters (SPMT's) with maximum axle capacity of 40 tonnes (Figure 5). Typically, 18 to 24 axles were used for each segment. The port mooring wall and waterside transit area were shared with cruise-liners and industrial operations.

Figure 5 – Off-loading and yard transportation on SPMT's.

Figure 6 – Preparation of formwork for pre-casting the deck slab.

An existing portal-framed shed about 300m from the water's edge, 154m x 57m plan dimensions, was modified to provide two enclosed deck pre-casting cells, a tower and pier reinforcement assembly area, formwork carpentry area and a concrete testing laboratory.

Alongside this building a concrete batching plant was built, with a capacity of 120m^3 per hour. The pre-casting cells could each accommodate one segment, transported in and out on SPMT's and supported on plinths with sliding bearings to allow very close tolerance positioning. Formwork for the cantilever slabs was pre-assembled and built on rails to move aside and allow entry and exit of the deck segment (Figure 6).

On the external storage yard, approximately 400m x 300m, 364 piled foundations were constructed to support the temporary works, steel-only segments and completed deck segments with concrete deck. Temporary, moveable support plinths were also used. The SPMT's ran precisely in the spaces between these plinths (Figure 7).

Figure 7 – Storage yard with some complete segments ready for load-out.

The tower falsework and four segments at each tower were installed by Taklift 6, equipped with a 130m boom, during October/November 2014. The deck erection gantries were partly installed on the tower segments at this stage. The falsework at each tower was lifted in four preassembled pieces, two leg structures and two supporting table structures (Figure 8).

Figure 8 – Taklift 6 installed falsework, tower segments and erection gantries.

Once the falsework was in place, with connections to tower and foundations completed, the first four deck segments (steelwork only) at each tower were erected and positioned to within 50 mm of the desired position. A jacking system installed as part of the falsework allowed full adjustment of line and level, which once concluded permitted the deck segment welding and concreting to proceed. The significant increase in loading due to concrete weight and the corresponding deformations of the falsework were countered by pre-setting the segment position and adjustments before each concrete pour.

Concreting of the deck and the fixed connection to the central tower, known as the “power joint” were executed and the first cable-stays installed. At the flanking towers, where the deck moves relative to the tower in the final condition, temporary bearings were installed in order to fix the longitudinal, transverse and rotating movements of these cantilevers during deck erection. The erection gantries were commissioned, the tower falsework jacking support system was lowered clear of the deck and the deck erection by balanced cantilever method commenced. At the power joint, the rigid connection between deck and central tower, special supports were installed so that the falsework could be unloaded without having to jack up first.

From the storage yard, load-out of the deck segments, now weighing up to almost 800 tonnes after concreting, was via purpose-built link-span bridges onto two modified barges, 91m long and 3100 tonnes gross weight. Each barge could carry two segments.

From the port, the barges were tugged the 3km to the bridge site and moored in the river at the precise lift location with the aid of four anchors. Operations on the water were sequenced in order to always provide unhindered shipping.

The deck-lifting cycle was optimised at seven days, during which the deck lifting, temporary connection, welding, concrete infill and cable-stay installation were completed, in preparation for lifting the next segment.

The erection gantry specifically designed for this bridge construction, was a single centrally positioned gantry, equipped with a travelling system to lift itself onto tracks and move forward (Figure 9). A cross head gantry, with longitudinal and transverse adjustment. supported two 588 tonne SWL strand jacks, complete with strand coilers, capable of lifting the heaviest segment at 784 tonnes, through the height of up to 60m in four hours. An adjustable lifting frame connected to the deck segment on the barge controlled the pitch of the segment, which varied throughout the cantilever construction. Movements of the cantilever and barge due to wind and waves were carefully monitored to be within the design parameters of the gantry. Design of the bridge included for the possibility of dropping a deck segment during erection and the erection gantry was designed such that it would not damage the bridge in this eventuality.

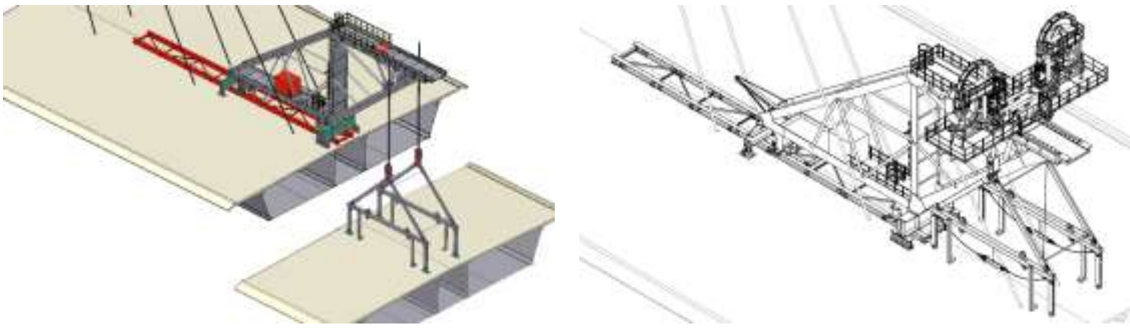

Figure 9 – Illustrative diagrams of the erection gantry.

All skin plate and flange welds for deck to deck connection were single sided full penetration butt welds. The trough and flat stiffeners were spliced with bolted connections. The welding sequence included a 24 hour cooling period prior to testing of all welds. At a calculated point, cable stay installation could start. A 700mm wide post-tensioned concrete infill, known as the “stitch”, was cast. Welding, stay installation and concrete strength were monitored and controlled until the erection gantry load could be released, and the stays would be finally tensioned prior to advancing the erection gantry to the next lifting position.

Moving gantries suspended below the deck allowed access to the external underside of the deck to assist in the deck connection and painting.

A standard balanced cantilever sequence was employed for the deck construction (Figure 10) with some notable variations. Each cantilever was strengthened by the installation of four temporary stays connecting the 5th and 6th segments to the tower foundation. These stays, on one cantilevering side only, provided addition overturning resistance to the cantilever during the unbalanced condition, which eventually achieved a maximum balanced cantilever length of 644m.

Figure 10 – First deck segment lifted by erection gantry, continuing with balanced cantilever construction.

Figure 11 – Balanced cantilever erection from all towers up to the first pier pass.

To the south, the cable-stayed bridge passed over two piers before arriving at the southern approach viaduct. Temporary works were installed on the tops of these piers in order to permit the typical erection method to continue. The deck segment immediately beyond the pier was lifted and translated southwards on the temporary works to await the lifting of the pier segment and both were supported on the piers. A connection was made between the cantilever deck, similar to a deck closure sequence, and once the deck continuity over and beyond the pier was complete the erection gantry could move itself forward and execute the next typical segment lift off the water (Figure 11).
The North Approach Viaduct (AVN), about 221m overall length, was fabricated in England as separate panels. This viaduct would be launched using a strand jack system, in two stages, from an assembly and launching area immediately north of the bridge. During tender a falsework support had been conceived whereby Taklift 6 would place the segments which would then be skidded into position over the falsework. Studies

after contract award showed the launch method to be superior in both cost and programme.

Figure 12 - North viaduct during assembly and launching.

The AVN steelwork was assembled on the launch pad and a temporary mast erected, using strand jacks (Figure 12). A strand jack launching system pulled the bridge forward to a point just before arrival at the first pier, N2. Here a rotation was carried out and further launching over N2 and N1, where sliding bearings positioned on the pier top temporary structures allowed launching to 1.0m short of the final position (Figure 13).

Figure 13 – North viaduct during assembly and launching.

The overall launched weight was 6 300 tonnes, including some concrete deck acting as counterweight, up a gradient of 3.7 degrees.
With three fans of the cable-stayed bridge complete and the north and south viaducts launched to approximately 1.0m short of the final position, the deck closures were commenced. The closures to the main spans were performed by jacking the north or south fans away from the central tower, which permitted the installation of the main span deck closure segments. Jacking systems were located at the north and south towers to permit this. After the corresponding main span closure, the north and south viaducts were launched forward and closed to the main cable-stayed bridge deck. Cable stays were then completed on the AVN.

Conclusion

Traffic first crossed the bridge on 30^{th} August 2017 prior to the official opening on 4^{th} September 2017 by Her Royal Highness, Queen Elizabeth II (Figure 14). In addition, celebratory bridge walks were held on 2^{nd} and 3^{rd} September when 50 000 people were allowed to cross the bridge on foot, and on 5^{th} September a community day was held enabling 10,000 members of the local community to walk on the bridge.

Figure 14 – Flyover during opening ceremony, and the completed bridge.

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